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Assessing Water Security and Coupling Coordination in the Lancang–Mekong River Basin for Sustainable Development

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Abstract: Water security is crucial for the sustainable development of regional water resources. Here, we utilize the Driver-Pressure-State-Impact-Response (DPSIR) framework to construct an indicator system for assessing water security in the Lancang–Mekong River Basin (LMRB). This study also delves into the level of development in the coupling coordination between the economic and social systems and the water resources systems in the basin. The findings reveal that the overall water security situation in the LMRB is satisfactory, with three countries (China, Laos, and Vietnam) surpassing the "safe" threshold and three countries (Thailand, Cambodia, and Myanmar) "Basically safe". However, water security issues persist, particularly in relation to water pollution and scarcity. Seasonal water shortages and water-related disasters arise due to uneven rainfall distribution throughout the year and inadequate regulating facilities such as wetlands and reservoirs. In addition, the overall coupling coordination level in the LMRB is low, ranging between 0.3 and 0.4, corresponding to a moderate imbalance level in the assessment criteria system. Specifically, Laos and China exhibit the highest coupling coordination level, with a degree of 0.36, whereas Thailand and Myanmar demonstrate the lowest level, with degrees of 0.33 and 0.31, respectively. Overall, our results offer a scientific foundation for the sustainable development of countries within the LMRB.

Keywords: transboundary rivers; Lancang–Mekong River Basin; DPSIR framework; water security assessment; coupling coordination degree

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1. Introduction

Water is vital for sustaining natural ecosystems and fostering social and economic development. However, global climate change has intensified the challenges facing water security by increasing demand, degrading quality, and reducing availability [1–3]. This poses a significant obstacle to regional and global development, impacting food and environmental security [4,5]. Assessing water security has become crucial for promoting comprehensive and harmonious regional development [6,7]. Given the multifaceted nature of water security, a holistic approach involving various sectors is necessary [8,9]. The challenge lies in determining a suitable index system and an effective quantitative assessment method that accommodates uncertainties arising from random and fuzzy conditions [10–12].

Traditional water security assessments rely on a single quantitative indicator, limiting their scope. Comprehensive indices, such as the Water Poverty Index (WPI) [13,14] and the Water Resources Carrying Capacity Equilibrium Index (IWSD) [15], aim to provide a more accurate assessment. A top-down approach, involving target, criterion, and indicator levels, has gained traction for regional water security assessments, offering specific and focused analyses [16–22]. The DPSIR framework, analyzing drivers, pressures, state, impacts, and responses, comprehensively captures the internal relationships in water systems [23,24]. Combining this framework with water security indicators ensures a systematic reflection of the regional water resources situation.

Crucially, weighting indicators is vital for comprehensive water security assessment, reflecting their relative importance [25,26]. Subjective methods, relying on expert judgment, and objective methods, utilizing mathematical approaches based on indicator data characteristics, are employed for this purpose [27–33]. Integrated water security assessment involves quantitatively evaluating the overall degree of water security in an area through systematic and standardized methods that assess multiple indicators simultaneously [34,35]. The assessment system in this study, based on the DPSIR framework, aligns well with the applicability of the fuzzy comprehensive evaluation method, especially "Single-index Quantification-Multi-index Comprehensive-Multi-criteria Integration Partner (SMI-P)".

Balancing water and socio-economic systems is crucial for regional water security. Rapid industrialization, urbanization, and population growth have increased water resource demand, leading to an imbalance between economic development and the water environment's carrying capacity [36]. Achieving sustainable development requires balancing economic growth and water security [37–39]. Recent studies emphasize assessing intrinsic linkages between economic growth and the environment to reveal development trends and patterns, maintaining ecological health while balancing resource development [40–42]. However, there is still relatively limited research on the coordinated development of water security and the economy.

The Lancang–Mekong River Basin (LMRB) connects China and five Southeast Asian countries, sharing interdependent ties regarding water resources, ecological environment maintenance, and biodiversity conservation [43–45]. This region faces challenges due to rapid economic development, population growth, and urbanization, causing an imbalance between increasing water demand and its scarcity [46,47]. Research related to the progress of Lancang–Mekong River Basin studies has mainly focused on changes in precipitation [48–50], cooperation in water resources and management [51–53], hydropower dam development [54,55], changes in runoff [56–59], droughts and floods [60,61], and the water-food-energy nexus in the basin [62,63]. Although these studies have analyzed different aspects of water security, the differences in water security among the six countries in the basin have largely been neglected. This study aims to establish a systematic water security assessment system, comparing indicators in six basin countries and highlighting differences in water security status. The study employs subjective and objective weighting methods to obtain rigorous and pragmatic results. The coupling coordination model assesses the relationship between subsystems, providing a scientific reference for effective regional water resource management.

2. Materials and Methods

2.1. Data

The LMRB is a transboundary basin involving six countries, which presents challenges in selecting data for water security indicators due to inconsistent data and standards among studies in these countries. To ensure the consistency and validity of the assessment results, we used publicly available and consistent data at the global level whenever possible and recognized the limitations of data accessibility (Table 1). As the study covers several countries and specific data scales, it was difficult to obtain long-time-series data from the same source for each country. Therefore, this study refers to the current water security situation in the LMRB. The water security assessment system includes dynamic and static indicators, as well as qualitative and quantitative ones. In such a situation, evaluating a base year may be unreasonable, and the indicators need to be analyzed for their ability to characterize the time scale. In this study, data indicators were classified as described previously. Multi-year averages were used for data on water hazards and their consequences due to their contingency and uncertainty. However, there are objective limitations in obtaining data on natural water quality on a global scale, and we therefore used the average of water quality indicators published by the World Bank from 1992 to 2010 to reflect the water quality of regional natural water bodies. Finally, the most recent data update was selected for the assessment of the status quo characterization category indicators to account for differences in the availability of different indicators.

2.2. Methods

This paper adopts a comprehensive approach to assessing water security in the LMRB. The first step is to select indicators and construct an assessment system based on the DPSIR framework. Next, a combination of subjective and objective methods, namely AHP hierarchical analysis and the entropy value method, is used to measure the weight of the indicators. The SMI-P method is then used to assess the state of water security and to identify issues in each country within the basin. Finally, a coupling coordination model is used to explore the factors affecting the coordinated development of the countries in the basin. Overall, the methods used in this study provide a robust framework for assessing water security in the LMRB and identifying issues for improvement. The specific methods involved in the above are as follows:

2.2.1. Indicator System Construction Method

This paper proposes a water security indicator system for the LMRB based on the DPSIR framework, where each subsystem is interconnected and mutually constrained [23,64]. The "Drivers" subsystem represents the fundamental human factors that can cause changes in water resources and the water environment, such as economic development, population growth, and urbanization. The "Pressure" subsystem is the result of the drivers and includes factors that may stress the water system and the water environment, including water use by each sector and water stress. The "State" subsystem reflects the water system and the water environment in the "Pressure" state, representing the assessment objectives, such as water quality, water quantity, and the state of the water environment. The "Response" subsystem represents the "Pressure", "State", and "Impact" subsystems, where relevant indicators are taken to respond to the state, mostly expressed as policy measures as well as legal and socio-economic instruments. By decoupling the feedback mechanisms among the modules of the DPSIR framework, this paper examines which human activities cause changes in the water system (D), how they affect the water system (P), what changes occur in the water system (S), what consequences they have (I), and how each country responds to the water security crisis (R). Figure 1 shows the internal linkages within the DPSIR framework.

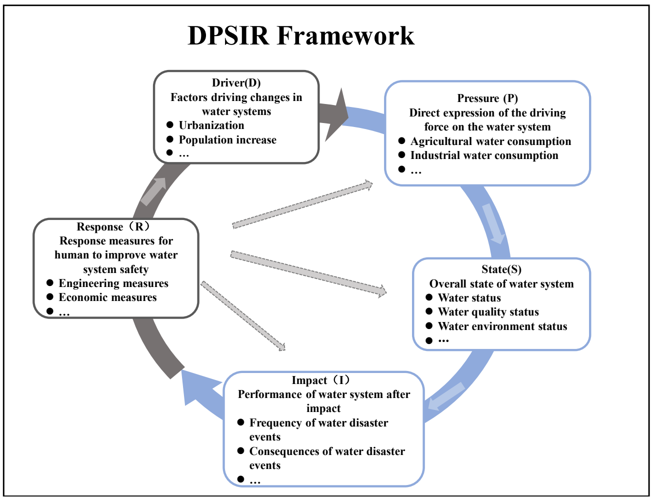

Figure 1. DPSIR (Driver-Pressure-State-Impact-Response) framework.

Table 1. Water security assessment indicator system of the LMRB and its data sources based on the DPSIR framework.

Target	Criterion	Indicator	Data Source
Water security Degree	Driver (D)	Population density (D1)	Gridded Population of the World Version 4 (GPWv4) (https://sedac.ciesin.columbia.edu/ accessed on 4 March 2022)
		GDP per capita (D2)	World Bank (https://data.worldbank.org.cn/, accessed on 6 March 2022)
		Urbanization rate (D3)	United Nations Population Division (https://www.un.org/, accessed on 22 April 2022)
	Pressures (P)	Agricultural water consumption (P1)	Report <Research on the capacity building of water quality improvement in Lancang–Mekong River countries>
		Domestic water consumption (P2)	
		Industrial water consumption (P3)	
		Water pressure (P4)	Water Environment Partnership in Asia (WEPA) (https://wepa-db.net/, accessed on 19 March 2022)
	State (S)	Average annual precipitation (S1)	Climatic Research Unit gridded Time Series (CRU TS) (https://crudata.uea.ac.uk/cru/data/hrg/, accessed on 11 March 2022)
		Average annual runoff (S2)	Transboundary Waters Assessment Plan (TWAP) (http://www.geftwap.org/, accessed on 27 March 2022)
		Proportion of wet season precipitation to annual precipitation (S3)	Climatic Research Unit gridded Time Series (CRU TS) (https://crudata.uea.ac.uk/cru/data/hrg/, accessed on 11 March 2022)
		Water biological oxygen demand (S4)	World Bank (https://data.worldbank.org.cn/, accessed on 14 April 2022)
		Water conductivity (S5)	
		Water nitrate–nitrite concentration (S6)	
		Forest coverage (S7)	Global Forest Cover Map (GFCM)
		Lake, reservoir, and wetland area (S8)	Global Lakes and Wetlands Database (GWLP) (https://www.worldwildlife.org/pages/global-lakes-and wetlands-database, accessed on 19 March 2022)
	Impact (I)	Drought frequency (I1)	Emergency Events Database (EM-DAT) (https://www.emdat.be/, accessed on 27 March 2022)
		Flood frequency (I2)	
		Deaths caused by water disasters (I3)	
		Economic losses caused by water disasters (I4)	
	Response (R)	Government funding for water sanitation (R1)	Organization for Economic Cooperation and Development (OECD) (https://www.oecd.org/, accessed on 15 March 2022)
		Proportion of population with access to improved drinking water (R2)	Joint Monitoring Programme (JMP) (https://washdata.org/, accessed on 6 April 2022)
		Proportion of sanitation facilities receiving basic improvements (3)	
		Wastewater treatment capacity (4)	HydroSHEDS database (https://www.hydrosheds.org/, accessed on 13 April 2022)
		Installed capacity of hydropower dam (R5)	Mekong River Commission (https://www.mrcmekong.org/, accessed on 23 April 2022)
		Reservoir capacity (R6)	
		Hydropower dam density (R7)	

DPSIR = Driver-Pressure-State-Impact-Response.

2.2.2. Indicator Weighting Method

This paper proposes a hybrid approach for determining the weights of water security assessment indicators in the LMRB, integrating subjective and objective weighting methods. The subjective weights are derived through the Analytic Hierarchy Process (AHP), while the objective weights are calculated using the Entropy Weight Method (EWM). Based on expert opinions and an extensive literature review, we assign equal importance (50:50 weighting) to each approach in the determination of indicator weights.

In applying the Analytic Hierarchy Process (AHP) to our research, we systematically decomposed the water security assessment into hierarchical levels of criteria and sub-criteria. Experts, possessing domain knowledge, provided pairwise comparisons of these criteria based on their perceived importance. The resulting comparative judgment matrix allowed us to calculate the subjective weights of each criterion. To ensure the reliability of the AHP results, we conducted a thorough compatibility check, involving the assessment of consistency in expert judgments. Any identified inconsistencies were addressed to refine the weights. The final outcome of the AHP process was a set of weights for each indicator, crucial for the overall assessment of water security in the LMRB.

For the Entropy Weight Method (EWM), our application involved determining the objective weights of water security indicators based on their impact on the LMRB system. We calculated the information entropy for each indicator, utilizing this measure to quantify the degree of disorder or variability that each indicator introduced into the assessment. Indicators with lower information entropy, indicating a higher degree of information and system variation, were assigned greater weights in the evaluation. Conversely, indicators with higher information entropy, signifying lower information content, received lower weights. This process ensured that the EWM objectively reflected the indicators' contributions to the overall water security assessment.

2.2.3. Integrated Water Security Assessment Method

This paper assesses the water security status of countries in the Mekong Basin using the Single-index Quantification-Multi-index Comprehensive-Multi-criteria Integration Partner (SMI-P) method of fuzzy integrated assessment. First, we quantify the indicators at the single indicator level and identify their differences among the different countries in the basin, based on their characteristic values. Second, we combine the weight values calculated at the criterion level with the quantified indicators, based on the quantification of individual indicators, to calculate the degree of certainty for each quasi-measurement level. Finally, we perform a multi-criteria synthesis to calculate the overall water security level for each country in the basin, determine the water security level, and identify the water security status.

(1) Single-index quantification

The classification of eigenvalue criteria for water security assessment is a critical step in quantifying individual indicators. In this study, segmented linear affiliation measures are used to assess the sub-security of each indicator on a scale of 0 to 1. The values of a, b, c, d, and e correspond to the worst, worse, pass, better, and optimal levels of each indicator, respectively. The sub-safety level of positive indicators increases with increasing values, whereas the sub-safety level of negative indicators decreases. The equation is as follows [65]:

$$ISD_i = \begin{cases} 0, & x_i \le a_i \\ 0.3\left(\frac{x_i - a_i}{b_i - a_i}\right), & a_i < x_i \le b_i \\ 0.3 + 0.3\left(\frac{x_i - b_i}{c_i - b_i}\right), & b_i < x_i \le c_i \\ 0.6 + 0.2\left(\frac{x_i - c_i}{d_i - c_i}\right), & c_i < x_i \le d_i \\ 0.8 + 0.2\left(\frac{x_i - d_i}{e_i - d_i}\right), & d_i < x_i \le e_i \\ 1, & x_i > e_i \end{cases}, \quad (1)$$

$$ISD_k = \begin{cases} 1, & x_k < e_k \\ 0.8 + 0.2\left(\frac{x_k - d_k}{e_k - d_k}\right), & e_k \le x_k < d_k \\ 0.6 + 0.2\left(\frac{x_k - c_k}{d_k - c_k}\right), & d_k \le x_k < c_k \\ 0.3 + 0.3\left(\frac{x_k - b_k}{c_k - b_k}\right), & c_k \le x_k < b_k \\ 0.3\left(\frac{x_k - a_k}{b_k - a_k}\right), & b_k \le x_k < a_k \\ 0, & x_k \ge a_k \end{cases}, \tag{2}$$

As the LMRB is a transboundary river, the assessment indicators used in this study should be consistent with international consensus or common practice, such as the Transboundary Waters Assessment Programme and the World Resources Institute reports. In addition, the selection of water security assessment indicators must consider regional characteristics and may be based on current values and trends in similar river systems. Notably, the assessment indicators in this study are relatively complex, and some of them lack quantitative classification criteria. Therefore, this paper draws on domestic and international research and considers the unique circumstances of the LMRB.

Specifically, the Transboundary Waters Assessment Programme (TWAP) report on the Lancang–Mekong River from the United Nations Environment Programme is used to assess average annual runoff, reservoir capacity, the density of hydropower dams, and other indicators. The proportion of the population with access to safe drinking water and basic sanitation is based on reports from the WHO/UNICEF Joint Monitoring Programme (JMP) on Water Supply, Sanitation, and Hygiene. Government investment in water and sanitation is classified according to World Bank standards for developing countries. The original EM-DAT database and the "1989–2018 dataset of typical cases of major global flood disasters" are used, among others, to classify indicators related to the frequency of droughts and floods, the number of deaths caused by water-related disasters, and the economic losses caused by water-related disasters. Water stress is assessed based on the ratio of water demand to available water, with allocation standards taken from the Water Environment Partnership in Asia (WEPA) and the report "Capacity Building for Water Quality Improvement in Lancang–Mekong Countries". The classification of water quality indicators varies widely among countries. In this study, the World Bank values for biological oxygen demand, conductivity, and nitrate–nitrite concentration in Southeast Asian rivers are used as the standards for classification. For the classification of the indicator "area of lakes, reservoirs, and wetlands", the proportion of these areas in the basin is used instead of the area of the LMRB alone. Population density, GDP per capita, and urbanization rate are classified based on the World Resources Institute's (WRI) "Water Security" section.

(2) Comprehensive multi-index

The index weight determined by the subjective and objective weighting methods is used to calculate the security levels of the five criteria layers in the DPSIR framework, using the following equations:

$$WD = \sum_{k=1}^{n1} w_k ISD_k, \tag{3}$$

$$WP = \sum_{k=1}^{n2} w_k ISD_k, \tag{4}$$

$$WS = \sum_{k=1}^{n3} w_k ISD_k, \tag{5}$$

$$WI = \sum_{k=1}^{n4} w_k ISD_k, \tag{6}$$

$$WR = \sum_{k=1}^{n5} w_k ISD_k, \tag{7}$$

where WD, WP, WS, WI, and WP are the security degrees of each criterion layer; w_k is the kth indicator weight; and $n1$, $n2$, $n3$, $n4$, and $n5$ are the numbers of classification of each layer.

(3) Multi-criteria synthesis

The security level of the target layer in the DPSIR framework is calculated using the weight of the criterion layer as determined by the subjective and objective weighting methods. The equation is as follows:

$$WSD = \beta_1 WD + \beta_2 WP + \beta_3 WS + \beta_4 WI + \beta_5 WR, \quad (8)$$

where WSD (Water security Degree) is the total regional water security, and β_1, β_2, β_3, β_4, and β_5 are the weights of each criterion layer. Based on relevant studies [66,67], water security is classified into five levels (Table 2).

Table 2. Range of values of the total regional water security.

Water Security Level	Value Range of the WSD
Very safe	0.81–1.00
Safe	0.61–0.80
Basically safe	0.41–0.60
Unsafe	0.21–0.40
Seriously unsafe	0.00–0.20

WSD: Water security Degree.

2.2.4. Coupling Coordination Method

The coupling coordination degree model is a useful tool to analyze the degree of the coordinated development in different systems. It measures the dynamic correlation between two or more systems that interact and influence each other, reflecting the degree of interdependence and mutual constraints between the systems [41]. In the context of the DPSIR model, the five criterion layers of drivers, pressure, state, impact, and response are interrelated and mutually constrained, and the coupling coordination degree model can be used to quantitatively measure the degree of coordinated development among these subsystems. Moreover, the model can identify the lagging system, which refers to the subsystem that impedes the overall coordinated development [40,42,68]. The model involves the calculation of three index values: the coupling degree (C), the coordination index (T), and the coupling coordination degree (D). In this paper, we refer to previous studies for the categorization of the coupling coordination into five types and three stages of development based on relevant studies [69–71], as presented in Table 3. The equation for calculating the coupling coordination degree is as follows [72]:

$$C = \frac{5\sqrt[5]{U_D U_P U_S U_I U_R}}{U_D + U_P + U_S + U_I + U_R} \quad (9)$$

where U_D, U_P, U_S, U_{DI}, and U_{DR} correspond to the integrated values of the DPSIR framework's driver, pressure, state, impact, and response subsystem, respectively. To ensure consistency, the integrated values of each subsystem are determined based on the method described in Section 2.2.3, using the following equation:

$$T = \alpha_1 U_D + \alpha_2 U_P + \alpha_3 U_S + \alpha_4 U_I + \alpha_5 U_R, \quad (10)$$

where α_1, α_2, α_3, α_4, and α_5 denote the contribution of each subsystem to the level of coordinated regional water security. In this study, it is assumed that each subsystem is equally significant in the coordinated development of regional water security, and thus, $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = \alpha_5 = 0.2$. The equation is as follows:

$$D = \sqrt{C \times T}, \quad (11)$$

Table 3. Classifications of coupling coordination degrees.

Coupling Coordination Degree	Type	Development Stage
$D \in [0.0, 0.2]$	Serious imbalance	
$D \in [0.2, 0.4)$	Moderate imbalance	Unbalanced development stage
$D \in [0.4, 0.5)$	Basic coordination	
$D \in [0.5, 0.8)$	Moderate coordination	Transitional development stage
$D \in [0.8, 1.0]$	Good coordination	Balanced development stage

3. Results

3.1. Analysis of the Indicator Weighting Results

Based on the DPSIR framework, a combination of the AHP and the EWM was employed to assign weights to 26 water security indicators in the LMRB. Figure 2 shows the calculation results. From the perspective of the criterion level, the weight distribution was mainly concentrated on the State layer (0.2689) and the Response layer (0.2974), followed by the Impact layer and the Pressure layer, with weights of 0.1785 and 0.1435, respectively. The lowest weight was calculated for the Driver layer (0.1143).

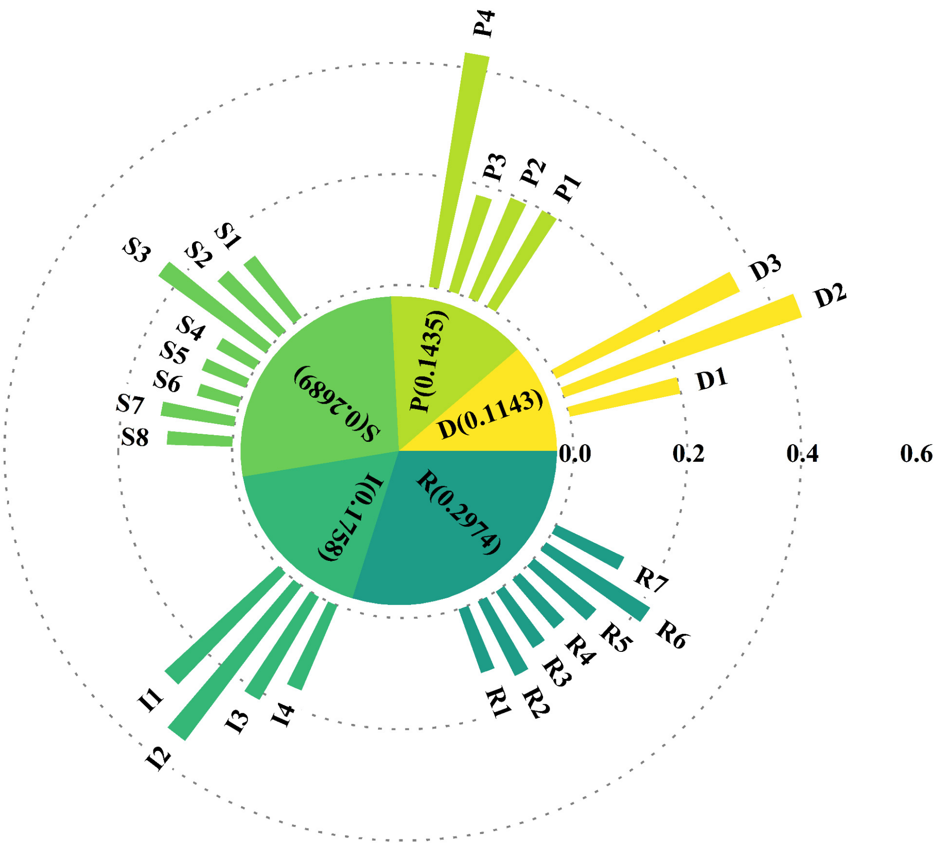

Figure 2. Calculation results for the weights of each indicator under the DPSIR model. DPSIR = Driver-Pressure-State-Impact-Response.

The State layer had a weight of 0.2689, and the proportion of wet season precipitation to annual precipitation had the highest weight (0.2340), emphasizing the impact of seasonal precipitation on regional water security. Forest cover, lakes, reservoirs, and wetlands had weights of 0.1306 and 0.1106, respectively, highlighting the significant impact of the water environment status within the basin. The Response layer had a weight of 0.2974, with the reservoir capacity indicator having the highest weight (0.2174). Human activities related to water management and system improvement were critical to ensuring water security. In the

Impact layer, the frequency of flooding had the highest weight (0.3460), and the weight of drought frequency was 0.2758, reflecting the high impact of droughts on the regional water security in the basin. The Pressure layer had a weight of 0.1435, and the weight of water pressure was 0.4264, indicating that the ratio of regional water demand to available water is an important factor affecting regional water security. The Driver layer was mainly driven by the GDP per capita (0.4422) and the urbanization rate (0.3590), reflecting the strong impact of economic development on water systems and the environment in the LMRB.

3.2. Comprehensive Assessment of Water Security in the Lancang–Mekong River Basin

Water security in the LMRB was assessed using the AHP and the EWM to obtain the combined subjective and objective weighting results. The Single-index Quantification-Multi-index Comprehensive-Multi-criteria Integration Partner (SMI-P) method was then employed to assess the water security level of each country in the basin. Overall, the water security in the basin is good and above the "safe" line, with Laos having the best water security, followed by China and Vietnam, which are rated as "safe". Cambodia, Thailand, and Myanmar have a relatively low level of water security and are in a "basically safe" state, indicating a less optimistic water security situation. Due to differences in geographical location, economic development, degree of water resource development, and focus of the basin countries, each country's water security presents a different state, with differences in the factors affecting water security issues. Figure 3 shows the results of the water security assessment for the Lancang–Mekong countries.

Specially, the water security level in Laos is considered "safe" at 0.702, with the Impact and Response criterion layers ranging from 0.15 to 0.20, indicating effective water security management and a relatively comprehensive water security system. However, the socio-economic development of Laos is exerting significant pressure on regional water resources, which is reflected in a low Driving criterion layer of 0.067. This leads to changes in the water environment, resulting in lower water security scores (0.132 and 0.135) in the Pressure and State criterion layers, respectively. China had an overall water security score of 0.655, also classified as 'safe', with a response criterion score of 0.203, the highest in the entire basin, suggesting that China's water security capabilities and related capacity building are complete and meet the water security needs. However, the country's socio-economic development resulted in increased water use pressure and changed water resource conditions, which has led to low water security scores of 0.109 and 0.087 in the Pressure and State criterion layers, respectively. Vietnam's overall water security level was 0.617, with the Driver criterion layer having the lowest value in the entire basin (0.056), indicating that uncontrolled socio-economic development is a significant cause of regional water security issues. In addition, Vietnam's water security Impact criterion layer was low, making regional water security vulnerable to water hazards. However, the country's water security Response criterion level was high at 0.175, indicating a strong regional water security capacity. Cambodia, on the other hand, is rich in water resources, with numerous lakes, reservoirs, and wetlands, high forest cover, and good water retention and renewal capacity. Cambodia's water quality and environment are in good condition, and the corresponding State criterion level for water security was therefore high (0.153). In addition, Cambodia has a low economic development level and low regional water stress, which resulted in a high water security level with a Pressure score of 0.134. However, Cambodia's water infrastructure is poor, and its water management capacity is weak, leading to a Response criterion score of 0.073. Thailand's water security level was classified as 'basically safe', with a score of 0.554, with the Pressure and Impact criteria scores being the lowest in the basin (0.074 and 0.094, respectively). This indicates that the country's abundant economic and water resources have resulted in a water-dependent economy and intensive economic activity, leading to high water stress and greater negative impacts of water-related disasters. Finally, Myanmar had the lowest water security level in the basin, with a score of 0.528, also classified as "basically safe". Although Myanmar's low economic level resulted in low water pressure, with a level of 0.143, it was the highest in the basin. Due to economic constraints, Myanmar is still under pressure and faces water security challenges, with the lowest water security score in the basin (0.061), which is insufficient to meet the regional water security needs.

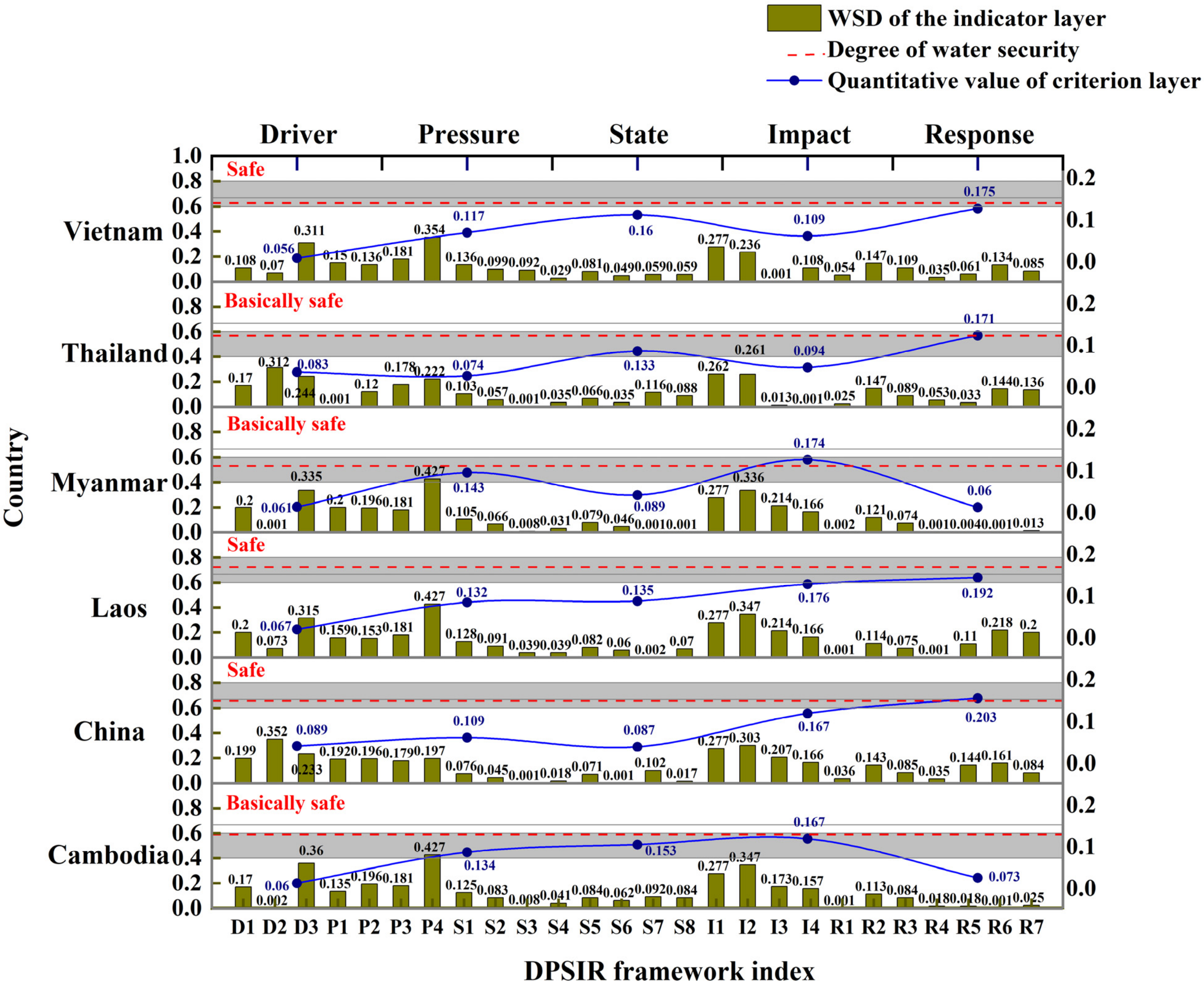

Figure 3. Results of water security assessment of Lancang–Mekong countries. DPSIR = Driver-Pressure-State-Impact-Response, WSD = Water security Degree.

3.3. Analysis of the Coupling Coordination Degree between Water Security Subsystems in the Lancang–Mekong River Basin

Water security is essential for sustainable economic development, and achieving a coordinated development between water resources and socio-economics is crucial to ensure water security. In this study, we propose a coupled coordination model to explain the interrelationships between the subsystems of the DPSIR framework. This model quantitatively reflects the degree of coordination in the "socio-economics-water stress-water status-water disasters-water management" system, which can help to assess the rationality of the regional economic development model, water resources development and use, and water resources management capacity. The coupled coordination model consists of two main components: the degree of coupling between systems and the degree of coordination between systems. The coupling degree is calculated by measuring the distance between systems to determine the coupling situation. The degree of coordination is calculated by the relative deviation coefficient to determine the degree of coordination. Figure 4 shows the results of the degree of coordination analysis.

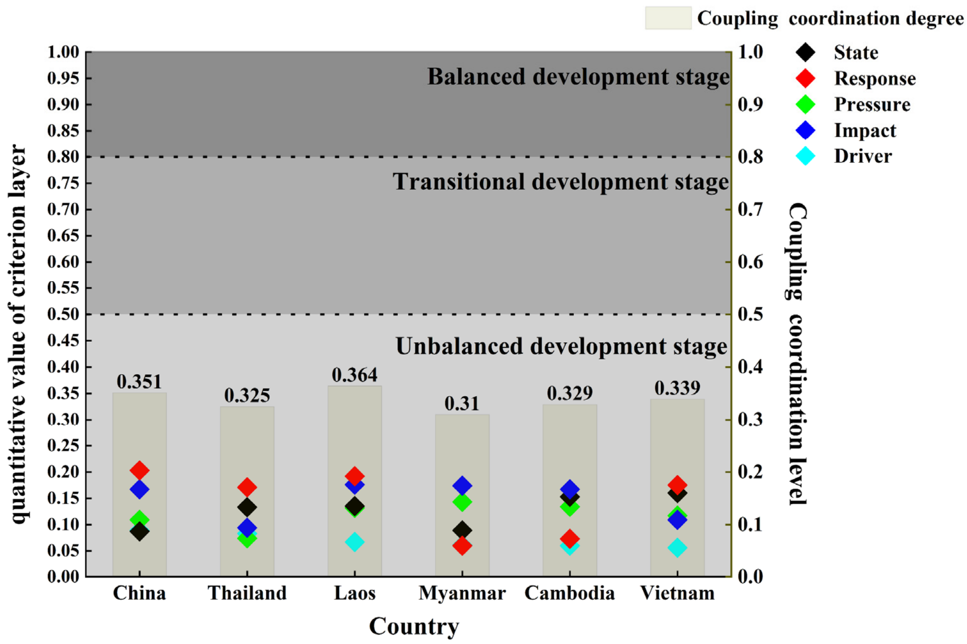

Figure 4. Coupling coordination and development stages of each country in the Lancang–Mekong River Basin.

Overall, the Lancang–Mekong River Basin has a low level of coupling coordination, with a degree of coupling coordination between 0.3 and 0.4. This level corresponds to the moderate imbalance level of the assessment criterion system. Specifically, the coordination between "socio-economic-water stress-water condition-water disaster-water response" is unbalanced. Among the countries in the basin, Laos and China had the highest level of coupling and coordination, with a coupling and coordination degree of 0.364 and 0.361, respectively, followed by Vietnam and Cambodia with a coupling and coordination degree of 0.339 and 0.329, respectively. In contrast, Thailand and Myanmar had the lowest levels of coupling and coordination, with a coupling and coordination degree of 0.325 and 0.310, respectively.

4. Discussion

4.1. Constraints to Water Security in the Lancang–Mekong River Basin

The Lancang–Mekong Basin water security assessment analyzes the current state of water security in the basin countries and identifies the constraints affecting it. With economic development, population growth, and climate change affecting the region, water security issues are becoming increasingly serious. The water security assessment shows that the identified constraints are consistent with the actual water security issues in the basin countries, indicating that a water security assessment system based on the DPSIR framework is appropriate. By combining the AHP and the EWM for subjective and objective indicator weighting and using the comprehensive assessment method of single indicator quantification-multi-criteria synthesis-multi-criteria synthesis (SMI-P), the approach is both scientific and feasible. The assessment results are objective and valid, making the identification and analysis of water security constraints based on the assessment results a crucial step in the protection and regulation of regional water security.

Water security in the Lancang–Mekong Basin is mainly influenced by three factors: climate, economic development, and water infrastructure. Climate, which varies across the basin, is a critical element affecting water security. The highland mountain, subtropical monsoon, and tropical monsoon areas have high rainfall but an uneven intra-annual rainfall distribution, resulting in an indicator "intra-annual rainfall distribution" of less than 0.1. Climate is therefore a key factor affecting water security in the Mekong River Basin. Economic development is also an important component of water security in the Lancang–

Mekong Basin. With increasing economic development, the level of government investment in water and sanitation, the proportion of the population with access to improved drinking water, and access to basic sanitation also increase. Although there is a positive correlation between economic development and regional water supply and sanitation, water quality indicators such as 'biological oxygen demand' and 'electrical conductivity' are negatively correlated with the level of economic development. The higher the level of economic development, the lower the quantified value of these indicators and, consequently, of the regional water quality. Water infrastructure is another critical component of water security in the Lancang–Mekong Basin. The better the 'response' to water security, the better the ability to maintain water security in the basin. Laos and China had higher water security scores of 0.528 and 0.389, respectively, than the other four countries in the basin, mainly because of their good water infrastructure and, as a result, higher water management capacity.

The Lancang–Mekong River Basin is home to a diverse range of countries, each facing unique water security constraints. For example, the Lancang River area in China, for instance, has a large undulating terrain, mostly high mountains and valleys, with a small area of lakes and wetlands. Due to this topography, the river has a weak natural water regulation capacity, as indicated by a score of only 0.017 for indicator S8 (Lake, reservoir, and wetland area) [73]. The rapid economic development of the region also had a negative impact on water quality, with indicators S4 (Water biological oxygen demand), S5 (Water conductivity), and S6 (Water nitrate–nitrite concentration) showing a relatively poor water quality, scoring only 0.018, 0.071, and 0.001, respectively [55,74]. Despite abundant precipitation, the Lancang River Basin is prone to droughts, particularly in the spring season. This is because of burning winds, which cause low precipitation levels and frequent droughts, resulting in considerable economic losses. Indicators I1 (Drought frequency) and I4 (Economic losses caused by water disasters) scored 0.277 and 0.166, respectively, suggesting a high frequency of droughts and economic losses in the region. The large agricultural area in the Lancang River Basin makes the economic losses from droughts even greater, particularly as drought-induced agricultural losses occur [75]. Lao PDR, on the other hand, has a low economic development level and a low population density, with most of its inhabitants living in rural areas. Unfortunately, the country also has low safety values of R2 (Proportion of population with access to improved drinking water) and R3 (Proportion of sanitation facilities receiving basic improvements), which characterize safe drinking water, scoring only 0.114 and 0.075, respectively. This makes the health issues of the population caused by drinking water more prominent [76]. Additionally, the wastewater treatment capacity in Laos is poor, with a quantitative indicator of only 0.001, the lowest in the entire basin. Based on previous studies, rural sanitation in Laos was only 36% in 2004, with only 0.1% of flushing toilets having septic tanks or sewerage systems [77,78].

Myanmar's economy is dominated by the primary sector, and changes in land use have led to the conversion of a large proportion of former forested areas into arable and mining areas. This has inevitably led to the deterioration of the water environment and, thus, affected water quality. Furthermore, the construction of infrastructure, such as the sewerage network collection system, is lagging behind, with indicator R4 (Wastewater treatment capacity) scoring only 0.001, exacerbating the outstanding water quality issues in the Myanmar section [79,80]. The Lancang–Mekong section in Myanmar is relatively short and a border river, with only some small hydropower stations and indicators R5 (Installed capacity of hydropower dam), R6 (Reservoir capacity), and R7 (Hydropower dam density) scoring only 0.110, 0.218, and 0.200, respectively. The low water infrastructure development level has resulted in a weak response to changes in the water environment and water security conditions [81,82].

In Thailand, the combination of a high economic level, a growing population, and accelerated urbanization has led to high water stress, making the stress criterion layers P1 (Agricultural water consumption), P2 (Domestic water consumption), P3 (Industrial water consumption), and P4 (Water pressure) those with the lowest values in the basin, with 0.001, 0.120, 0.178, and 0.222, respectively, with high regional water demand. According to previous studies, Thailand faces a conflicting water supply and demand during its dry season due to a weak water regulation capacity and a high-water demand [83–86]. In addition, the frequent occurrence of water hazards in Thailand and their negative impacts are important constraints on the regional water security, with indicators I2 (Flood frequency) and I4 (Economic losses caused by water disasters) having the lowest values in the basin (0.261 and 0.001, respectively). This is mainly since Thailand's precipitation is concentrated in the wet season, which receives 85–90% of the annual precipitation and 75–80% of the annual runoff, resulting in frequent flooding. The combination of a high economic activity intensity, a high population density, and large irrigated areas exacerbates the severity of the impacts of flooding, leading to severe economic losses and human fatalities [87–89].

Cambodia, on the other hand, is rich in water resources, but they are unevenly distributed throughout the year, with indicator S3 (Proportion of wet season precipitation to annual precipitation) having a value of only 0.008. Cambodia receives very little precipitation and annual runoff during the dry season (December to April) and therefore relies heavily on water storage projects for water extraction and use. However, the country only has a small number of water and hydropower plants, and indicators R5 (Installed capacity of hydropower dam), R6 (Reservoir capacity), and R7 (Hydropower dam density) had values of only 0.018, 0.001, and 0.025, respectively. Cambodia has a low level of economic development, and water is mainly used for agriculture, with an indicator P1 (Agricultural water consumption) value of only 0.135. However, poor irrigation technology leads to serious water wastage, indirectly leading to high pressure on regional agricultural water use [90]. Cambodia is severely affected by water disasters, with indicators I3 (Deaths caused by water disasters) and I4 (Economic losses caused by water disasters) having values of only 0.173 and 0.157, respectively. This is mainly due to the high number of floods in Cambodia due to the combination of incoming water from upstream and local precipitation. The weak flood protection capacity of built reservoirs and hydropower dams exacerbates the severity of the impacts of flooding, leading to huge losses to life and properties [91–93].

Vietnam has achieved significant economic and social development, reflected by indicators D1 (Population density) and D2 (GDP per capita) with values of 0.108 and 0.070, respectively. However, the country's high population density and urbanization have led to increased water usage pressure, with negative impacts on the regional water security [94–96]. Water pollution is serious in Vietnam, with an S4 (Water biological oxygen demand) of 0.029, caused by the use of fertilizers in agriculture and industrial effluents in natural water bodies. The flat topography of the country, which is located in the lowermost reaches of the Lancang–Mekong River, mostly in the deltaic coastal areas, exacerbates pollution in natural water bodies [96]. Vietnam's fast-growing economy and high-intensity human activities have also caused changes in substrate conditions, such as forest cover, vegetation, and soil, as reflected by indicators S7 (Forest coverage) and S8 (Lake, reservoir, and wetland area), with values of only 0.059. Forest cover and lake wetlands are essential for water resources renewal and green development, but Vietnam's water environment is in poor condition [97]. Moreover, the country faces a significant threat from floods due to climate change and human activities, with indicators I2 (Flood frequency) and I3 (Deaths caused by water disasters) having values of only 0.236 and 0.001, respectively. The high frequency of floods due to a combination of intense precipitation, drainage from upstream reservoirs, and storm surges during high tides, combined with the facts that 70% of the country's terrestrial area is located at or below 500 m above sea level and that most of the economic activities and agricultural land are in low-lying areas, can increase the economic losses and mortality caused by floods [98]

4.2. Differences in the Coupling and Coordination of Water Security Systems and Lagging Systems between Countries

As a whole, the Lancang–Mekong River Basin is in a state of moderate imbalance, but there are differences in the coupling and coordination of water security systems and lagging systems between countries. Specifically, the coupling between the Chinese response system (0.203) and the impact system (0.167) is good and at a high level, suggesting that the frequency of water hazards and their negative impacts in the Lancang River Basin can be controlled and mitigated via relevant response measures [99,100]. However, China's state system (0.087) is lagging behind, suggesting that regional water quality and water environment are constraints to the coordinated development of water security in the Lancang River Basin [74,101,102]. The combined index of the Driver system (0.083), Pressure system (0.074), and Impact system (0.094) in Thailand is in a lagging state, indicating that the country's intensive economic activities and the development of the industrial and agricultural economy have led to an increased water demand, resulting in high regional water stress [103,104]. Economic activity and population density indirectly lead to higher economic losses because of water disasters, such as in the Chao Phraya River Basin, which is home to approximately 20 million people, 30% of Thailand's total population, and to most of the country's manufacturing industry; the flat topography of the basin can have significant negative impacts in the event of flooding [105,106]. According to data regarding insured losses because of natural catastrophes, in 2011, Thailand's economic losses because of flooding were among the highest in the world.

Laos' response system (0.192) is well coupled with the impact system (0.176) and state system (0.135) and at a high level of coordination, indicating that water management in Laos has reduced regional water hazards and improved the water environment and quality. For example, the construction of hydropower dams and other projects has facilitated the regulation of the abundance and balance of the spatial and temporal distribution of water resources, improving the country´s water security capacity and promoting coordinated regional development [107]. In contrast, Myanmar's response system (0.061) and driver system (0.061) lag behind. Due to the country´s low economic level, its water management capacity is limited, with a weak capacity to build hydropower dams and water storage facilities and a low level of integrated flood and water hazard management [108,109]. The Cambodian Driving force system (0.060) and Response system (0.073) also lag behind, and the country´s socio-economic factors are a major constraint to the coordinated development of the regional water security. Cambodia's regional economic development and population density indirectly lead to higher economic losses from water hazards, combined with a limited response capacity [110]. In Vietnam, the Driving force system (0.056) and the Impact system (0.109) are constraints to the coordinated development of the regional water security. High precipitation and its concentration in the rainy season lead to frequent regional water hazards, which, combined with the current status of Vietnam's agriculture-led economy, have enhanced the negative impacts of water hazards, representing a major obstacle to the coordinated development of regional coupling [93,109–111].

5. Conclusions

The Lancang–Mekong River is a significant transboundary river in Asia, but its development has been affected by differences in geography, economic development, and political systems of the riparian countries, leading to considerable disparities in water resource development. Additionally, climate change and human activities have exacerbated water security issues in the region. To evaluate water security in the LMRB, we used the DPSIR model to develop an assessment indicator system that takes into account various factors. The assessment found that while the overall water security in the LMRB is good and above the "safe" line, some issues require attention. Water pollution, water scarcity, and other issues have caused the water resources to be in a relatively low state, and seasonal water scarcity and water-related disasters are common. The riparian countries' responsiveness is limited, and the water resource management capacity needs improvement.

At the country level, each country faces unique challenges that affect their water security status. China's water status is safe, with drought-related water scarcity being the main concern, while Thailand's water status is "basically safe", facing factors such as climate-related flooding, uneven rainfall, and limited water storage capacity. Laos's water status is safe, but irrigation and industrial activities' pollution of natural water bodies and limited access to safe drinking water due to economic underdevelopment are challenging. Myanmar's water status is "basically safe", mainly because of the country's weak capacity to develop water resources, poor water quality, and the threat of flooding. Cambodia's water status is also "basically safe", facing low water use efficiency, dry-season water scarcity, low levels of water management for hydropower, and serious water quality issues. Vietnam's water status is safe, but the country faces frequent flooding and has a weak capacity to manage its water resources.

Finally, water security is crucial for sustainable economic development, and coordinated development between water resources and socio-economics is essential. However, the overall level of coupling coordination in the Lancang–Mekong River Basin is low, ranging from 0.3 to 0.4, corresponding to the moderate imbalance level of the scoring system. Laos and China have the highest levels of coupling and coordination, followed by Vietnam and Cambodia, while Thailand and Myanmar have a relatively lower level of coupling and coordination.

This study is subject to certain limitations. In the construction of water security indicators for the Mekong River Basin, our objective was to select indicators that authentically reflect the basin's specific conditions, ensuring a comprehensive assessment of water security. Although the constructed indicator system may not have universal applicability, it can function as a valuable reference for similar regions. Geological conditions in both the upstream and downstream areas play a pivotal role in regional water security, necessitating flexible adjustments based on the specific geological characteristics of each location. Given the transboundary nature of the Lancang–Mekong River Basin, obtaining extensive time series data for indicators poses a significant challenge. Consequently, the water security level assessed in this paper pertains specifically to the current state of water security in the basin countries, focusing on existing issues and analyzing influencing factors. Additionally, the assessment of 'water quality' in this study represents the current basin-wide status, without accounting for variations in water quality between upstream and downstream areas or the propagation process. Future research endeavors will delve into this aspect should dynamic water quality data become available.

In envisioning the future of water security in the Lancang–Mekong River Basin, several key strategies and mechanisms emerge to enhance regional resilience. The Belt and Road Initiative (BRI) serves as a promising avenue for fostering collaboration and resource-sharing among the basin countries. By promoting infrastructural development and connectivity, the BRI can contribute to improved water resource management and disaster resilience. The Lancang–Mekong Mechanism, an existing cooperative framework, is poised to play a crucial role in facilitating dialogue and coordination among member countries. Emphasizing data sharing is imperative, enabling a comprehensive understanding of the basin's dynamics and supporting evidence-based decision-making. Robust disaster monitoring systems should be established to enhance early warning capabilities, mitigating the impact of water-related disasters. Additionally, technological advancements and innovation in water resource monitoring can further bolster the region's capacity to address emerging challenges. As these initiatives converge, a holistic and collaborative approach can pave the way for sustainable water security in the Lancang–Mekong River Basin.

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